

Structure, Formation and Ages of Elliptical Galaxies

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Abstract:

The structural properties of elliptical galaxies are consistent with their formation in a merging hierarchy. In this picture, the role of gaseous processes and dissipation decreased with increasing mass creating preferentially rotationally flattened disk ellipticals (and S0s) at lower luminosities and boxy, anisotropic ellipticals (often with peculiar kinematics) at higher luminosities. However, gas and dissipation processes must have been important even in the formation of the most luminous ellipticals. They played key roles in determining the phase space structure of Es and possibly ensured a tight fundamental plane.

The bulk of the stars in the majority of *luminous* cluster ellipticals formed at redshifts above two, likely above three. This follows from their homogeneous colors and line strengths and their essentially passive evolution with redshift. Low luminosity ellipticals (and probably field ellipticals) may have had extended star formation histories, possibly associated with the presence of disks. The star-formation time-scales can presumably be constrained on the basis of abundance ratios and seem to be *inversely* related to galaxy mass. Massive ellipticals are likely to have formed the bulk of their stars within one Gigayear.

1. Introduction

Elliptical Galaxies can appear as complex individuals when we analyse their detailed structure and internal dynamics. But they can also behave highly uniformly when viewed under the perspective of global scaling properties or stellar populations. As will be discussed in this paper, these apparently disparate properties are keys to their nature and allow to put constraints on their formation histories and ages.

In Section 2, I review the varieties of structures we observe in ellipticals and analyse the relevance of dissipation and merging in their formation. In Section 3, I discuss a few aspects of the fundamental plane. In Sections 4 and 5, constraints on the ages and star formation time scales of ellipticals are derived on the basis of their stellar populations. In Section 6, I set out to higher redshift to check whether the inferences derived from the local population of ellipticals find confirmation in the evolution of their properties.

2. Structure and Formation Processes

There is convincing evidence that Es can be sub-divided into basically two groups with respect to their structural properties. One group is characterized by boxiness, anisotropy and shallow cores, the other by diskiness, rotational flattening and the absence of cores (e.g. Bender 1988a, 1990, Faber et al. 1997). It may well be that there exists a clear-cut separation between the two groups, but this is not clear yet.

Disk Es contain faint disks which contribute between a few percent and up to 30% to the total light of the galaxy (Rix & White 1990, Scorza & Bender 1995). Generally, the spheroids are rotationally supported and the angular momenta of disks and bulges are parallel to each other indicating a 'coordinated' formation (Bender et al. 1993). Recent HST imaging by Faber et al. (1997) has shown that disk Es also have high density power-law profiles that lack cores while boxy Es have shallow cores (confirming and extending earlier claims by Nieto et al. 1991). These data show that dissipation was essential for the formation of disk Es. They simply seem to form the continuation of the Hubble sequence to the lowest disk-to-bulge ratios (Bender 1988a, 1990, Kormendy & Bender 1996).

Boxy Es, on the other hand, are mostly supported by anisotropic velocity dispersions and frequently show hints for a formation dominated by merging processes (Nieto 1988, Bender & Surma 1992). Peculiar velocity fields, like minor axis rotation and kinematically decoupled cores (Franx & Illingworth 1988, Jedrezewski & Schechter 1988, Bender 1988b) are a natural by-product of merging of star-dominated systems (Hernquist & Barnes 1991; in a few cases they could also have other origins, see Statler 1994). Unlike shells or ripples (e.g., Schweizer 1990), these features are long-lived or permanent and carry 'genetic' information about the formation process of the main (i.e. inner) parts of the galaxy. Interestingly, disk and boxy Es are also separated by their radio and X-ray properties (Bender et al. 1989). This indicates interesting links between galaxy structure and the presence or feeding of black holes as well as the depth of the galaxies' potential wells.

The dynamical structure and the degree of peculiarity of the merger product are presumably strongly related to the gas content of the progenitors. Little gas seems to suffice to reduce the fraction of box orbits in the merger remnant in favor of z-axis tubes (Barnes & Hernquist 1996). Centrally concentrated gas, like central cusps, may also destabilize box orbits (Dubinski 1994). Since box orbits are the backbone of triaxial objects (see e.g. Merritt 1997), while z-tubes are dominant in rotationally flattened objects, the gas fraction in the progenitors must be a key factor in determining the structure of the merger remnant. Simply speaking, less gas implies a more exciting end product. In this sense, we cannot exclude that disk Es are merger products as well. We can only conclude that, if they are, gas has dominated sufficiently to remove all clear-cut evidence for their merger history.

In a hierarchical galaxy formation scenario galaxies are expected to form via

a sequence of merging and accretion processes (e.g. White 1995). Presumably, merging is also driving the star formation history (e.g. Katz 1992, Steinmetz & Müller 1994) depleting the gas with increasing galaxy mass. Therefore, the formation of the most massive galaxies involved rather little gas and dissipation. Consistent with this picture, the vast majority of boxy Es has luminosities above L_* , while the luminosity function of disk Es resembles the one of S0s (Bender et al. 1993).

The low-redshift analogue of the late formation-phase of boxy Es may be found in ultraluminous IRAS mergers (Schweizer 1990, Kormendy & Sanders 1992, Bender & Surma 1992). While violent relaxation in these objects will likely create a boxy main body (Steinmetz 1995), the molecular gas concentrates in the central kiloparsec and can form a kinematically decoupled core (Hernquist & Barnes 1991, Barnes 1996). Indeed, the masses and metallicities of kinematically decoupled cores in Es are quite similar to those of the central gas tori in IRAS mergers (Bender & Surma 1992). We can speculate that very gas-rich progenitors may also create disk Es. The analogy of E galaxy formation and the IRAS merging process is unlikely to be perfect. Especially, it does not necessarily imply that Es generally formed in spiral-spiral mergers at low redshift – merging of any star-dominated progenitors at any redshift may have produced similar remnants.

3. Fundamental Plane

Ellipticals define a two-dimensional manifold in the three-dimensional space of their global structural parameters (effective radius R_e , mean effective surface brightness $\langle SB \rangle_e$, velocity dispersion σ), the so-called fundamental plane (Djorgovski & Davis 1987, Dressler et al. 1987). Its defining relation is $\log R_e = 1.25 \log \sigma + 0.32 \langle SB \rangle_e + const.$ (e.g. Jørgensen et al. 1996). It seems to be independent from environment (Jørgensen et al. 1996) and is also valid for S0s and, with slight changes, for dwarf ellipticals, too (Bender, Burstein & Faber 1992). It is now generally agreed that the fundamental plane is simply a consequence of the Virial theorem and the fact that E galaxies have similar mass-to-light ratios and close to homologous structure at a given luminosity (e.g. Faber et al. 1987, Djorgovski et al. 1989, Bender, Burstein & Faber 1992). There are two aspects of the fundamental plane. Roughly speaking, the edge-on view is indicative of the degree of similarity between Es of a given luminosity, the face-on view provides information about formation processes and evolution.

Despite of the large variety of internal dynamics and structure, the scatter perpendicular to the fundamental plane is very small. Jørgensen et al. (1996) find a typical rms-scatter of 20% in R_e . In the case of the Coma cluster, the scatter is smaller than 10% (Saglia et al. 1993, 1997), which is quite surprising for such complex objects as Es (see Figure 1 below). One explanation for this regularity could be the presence of at least some gas in all merging events Es underwent (see above). If the gas fraction was always about the same at a given mass then Es of similar luminosity may have similar phase space structure despite of peculiar velocity fields (which may be just the frost on the cake —

however frost that carries the finger-prints of formation...). This notion is also supported by kinematic and photometric studies which suggest that ellipticals are only mildly triaxial and generally close to oblate (e.g. de Zeeuw & Franx 1991). This is significantly different from the prolate-triaxial shape of, e.g., dark matter halos formed in collisionless collapse (e.g. Frenk et al. 1988).

Renzini & Ciotti (1993), Ciotti et al. (1996), Graham & Colless (1997) and others have carried out detailed studies about the influence of various parameters on the scatter perpendicular to the fundamental plane. They derive interesting constraints on the ages, the initial mass function of the stars, the variation of dynamical structure and density distribution and on dark matter content. The implied small scatter in mass-to-light ratio constrains the variation of ages at a given luminosity significantly and is consistent with other indications based on colors and line-strengths (see next section). Graham & Colless (1997) find convincing evidence that the tilt of the fundamental plane relative to the simple virial relation is due to the systematic variation of surface brightness with luminosity.

Bender, Burstein & Faber (1992) have analysed the distribution of Es and other galaxies *within* the fundamental plane. The face-on view of the fundamental plane is very similar to the luminosity-surface-brightness diagram of Es. Together with bulges, E galaxies define a sequence in the plane that extends from high density, low luminosity objects like M32 to low density, high luminosity objects like M87. Several properties vary smoothly with mass along this sequence (though with significant scatter), including bulge-to-disk ratio, radio and X-ray properties, rotation, degree of velocity anisotropy, and peculiar kinematics. These trends are consistent with the idea that the final mergers leading to larger galaxies were systematically more stellar (and less gaseous) than those producing smaller galaxies, as discussed above. If compared with typical cold-dark-matter fluctuations, it also follows that the baryonic component in high luminosity Es dissipated less than the one of low luminosity Es.

4. Stellar Populations and Ages

The stellar populations of elliptical galaxies are surprisingly homogenous, consistent with the small scatter about the fundamental plane. Colors and line-strengths are generally one-to-one correlated and scale with luminosity or, even more tightly, with velocity dispersion σ (e.g. Burstein et al. 1988, Dressler et al. 1987, Bower et al. 1992, Bender, Burstein & Faber 1993). It is important to note that there is no difference in the Mg- σ relation between disk and boxy Es or between kinematically peculiar and regular Es. However, there are hints for a weak dependence of the color- σ and Mg- σ relations on the presence of rather short-lived peculiarities (due to accretion of younger stars, Schweizer et al. 1990) and, possibly, on environmental density (Lucey et al. 1993, Jørgensen 1997).

With stellar population synthesis models (e.g., Worthey 1994) one can estimate the combined scatter in age and metallicity from the observed scatter in

the color- σ or Mg- σ relations. Consistently, Bower et al. (1992) and Bender, Burstein & Faber (1993) found for *luminous cluster* Es that the scatter in age and/or metallicity at a fixed σ must be smaller than 15%. Evidently, luminous Es (independent of whether they are boxy or not) cannot have formed continuously over the Hubble time suggesting that they are old on average. High age and small metallicity spread are also required to explain the observed very high Mg-absorption in the central parts of Es (Greggio 1997).

The age constraints for field Es and lower luminosity Es, which mostly belong to the disk class, are much less tight due to small samples or larger scatter in Mg and colors at smaller σ . In fact, it is indicated that low-luminosity Es ($M_T \approx -18$) seem to be systematically younger than giant Es ($M_T \approx -21$), see Faber et al. (1995) and Worthey (1996). Note that this trend runs opposite to the one expected in a cold-dark-matter model (Kauffmann et al. 1994). The apparently smaller ages of low luminosity Es could in fact be caused by the faint disks they contain. These disks may become more dominant towards lower luminosities and may have had extended star formation histories. Hints for this have been found by de Jong & Davies (1996).

5. Abundance Ratios and Star Formation Time Scales

Another way to extract information about the star formation history of ellipticals is to analyse their element abundance ratios. For *luminous* Es, Worthey et al. (1992), Davies et al. (1993) and others found consistently that Mg is overabundant relative to Fe. Over a larger luminosity range, [Mg/Fe] seems to be correlated with velocity dispersion: faint Es have [Mg/Fe] ≈ 0 , while luminous Es reach [Mg/Fe] ≈ 0.4 (Gonzalez 1993, Fisher, Franx & Illingworth 1995). Furthermore, Paquet (1994) could show that, in luminous Es, other light elements like Na and CN are overabundant relative to Fe as well. Within the galaxies, the [Mg/Fe] overabundance is usually radially constant up to at least the effective radii (Davies et al. 1993, Paquet 1994). Generally, no distinction between 'normal' luminous Es and Es with kinematically decoupled cores is indicated. This implies that the enrichment history of luminous Es differed significantly from the one of the solar neighborhood, see e.g., Matteucci & Greggio (1986), Truran & Burkert (1995), Faber et al. (1995), Worthey (1996).

Evidently, the enrichment of *massive* (high velocity dispersion) Es was dominated by Supernovae II, as only they can produce a light element overabundance. Supernovae Ia basically just provide iron peak elements (see, e.g., Truran & Thielemann 1986). Because the yields of SNII integrated over a plausible IMF result in [Mg/Fe] ≈ 0.3 dex at most (see Thomas, Greggio & Bender 1997 who use the most up-to-date yield estimates), we can conclude that the contribution of SNIa to the enrichment of the most massive Es must have been small, if not negligible.

The prevalence of Supernovae II and in turn the light element overabundance in massive Es can have the following reasons: (a) a star formation time scale smaller than about 1Gyr (SNI explode in significant numbers only after a

few times 10^8 yrs after star formation started, e.g. Truran & Burkert 1995), (b) a top heavy initial mass function, (c) a reduced frequency of binary stars (leading to fewer SNI events). – Option (c) is rather unlikely because one expects the binary frequency to be determined by the local process of star formation rather than by global galaxy properties. In addition, a low binary fraction may be inconsistent with the observed frequency of discrete X-ray sources in old populations. Neither does option (b) work well, because the overabundance in massive Es reaches $[\text{Mg}/\text{Fe}] \approx 0.4$ dex (as is also observed in Galactic halo stars, Fuhrmann et al. 1995). For such high overabundances, a flat IMF alone cannot solve the overabundance problem. So, option (a), i.e. a short star formation time scale, seems to be necessary in any case. In their recent study, Thomas, Greggio & Bender (1997) show that the star formation time scale in massive Es was probably shorter than roughly 1 Gyr.

Note that these considerations do not only apply to the cores of luminous Es but for the bulk of their stars, since the $[\text{Mg}/\text{Fe}]$ overabundance is similar at all radii (see above). And another important conclusion can be drawn from these findings: since most present day spirals have gas-to-star ratios smaller than 0.2 and disk stars show solar element ratios, merging of objects similar to present-day spirals cannot produce objects similar to most present-day massive Es. However, even some luminous Es (e.g. NGC 5322) have $[\text{Mg}/\text{Fe}] \approx 0$ and could be late merger products.

Since lower luminosity ellipticals have smaller light-element overabundances, their star formation time scales are not severely constrained. In fact, solar element abundance ratios could be taken as a hint for extended star formation histories in smaller Es.

6. Redshift Evolution

The amount of data on luminous elliptical galaxies at intermediate and high redshifts is now rapidly increasing thanks to bigger telescopes and better instruments. This allows to study the evolution of their luminosities (Glazebrook et al. 1995, Lilly et al. 1996), colors (Aragon-Salamanca et al. 1993, Stanford et al. 1995) and surface brightnesses (Dickinson 1995, Pahre et al. 1996, Schade et al. 1996). The tightest constraints are derived on the basis of the $\text{Mg}-\sigma$ relation (Bender, Ziegler & Bruzual 1996) and the fundamental plane (Franx 1993, 1995, van Dokkum & Franx 1996, Bender et al. 1997). All data indicate that the redshift evolution of massive Es is very small and basically consistent with passive evolution of very old stellar populations, there is no evidence for dynamical evolution. The bulk of the stars in massive Es must have formed at redshifts $z > 2$, likely at $z > 3$.

As an example, Figure 1 shows the fundamental plane of Es in the clusters Abell 370 and MS1512+36 at $z = 0.375$. Details about the observational procedure can be found in Ziegler & Bender 1997 and Saglia et al. (1997). The surface brightness term has been transformed to rest-frame B-band and corrected for cosmological dimming $((1+z)^4)$. The difference between the fundamental plane

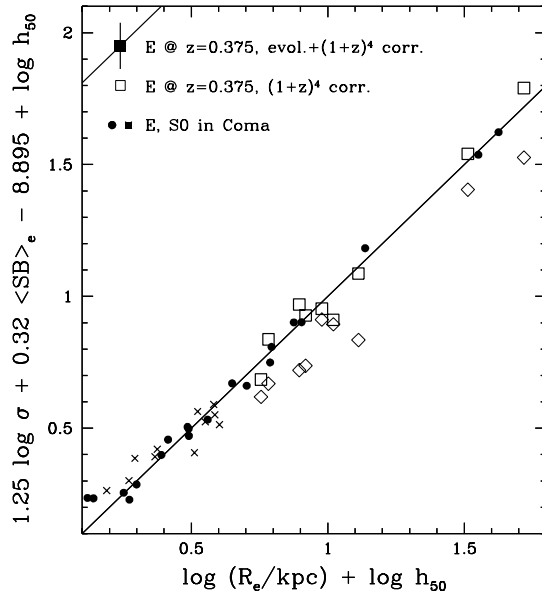


Figure 1. The Fundamental Plane of E and S0 galaxies. Small filled circles and small crosses denote E and S0 galaxies, respectively, in the Coma cluster with velocity dispersions $\sigma > 120$ km/s and effective radii R_e and effective surface brightnesses $\langle SB \rangle_e$ in the B band. The typical measurement errors are somewhat smaller than the scatter indicates. The open diamonds show Es at $z = 0.375$, also in rest-frame B-band and after surface brightness has been corrected for cosmological $(1+z)^4$ dimming. The open squares represent the $z = 0.375$ Es after further correction for luminosity evolution as derived from the $Mg_b - \sigma$ relation (see text). A typical error bar is shown for the $z = 0.375$ Es in the upper left. h_{50} is the Hubble constant in units of 50 km/s/Mpc. The Figure is adapted from Bender et al. (1997).

at $z = 0.375$ and in Coma is very small and is entirely accounted for by passive evolution. Passive evolution of the stellar population can be corrected for using the reduced Mg -absorption of distant Es as derived from the $Mg_b - \sigma$ relation. From Worthey's (1994) models one obtains the relation between Mg_b and B-band evolution: $\Delta B = 1.4\Delta Mg_b$ (Bender et al. 1997). Once this correction is applied, the Es at $z = 0.375$ fall on top of the Es in the Coma cluster.

It is important to note that these results on the redshift evolution of Es, and especially the most reliable ones, refer mostly to luminous Es or Es in clusters and so they may not apply to low luminosity Es or field Es. Indeed, there is a hint that at least in the Lilly et al. (1996) sample, which contains mostly bright field Es, the number density of Es evolves with redshift (Kauffmann et al. 1997). So, a sizable fraction of field Es could in principle still form at lower redshifts.

The evolution of Es in clusters cannot be discussed without considering the fate of blue cluster members and E+A galaxies in intermediate redshift clusters (Butcher & Oemler 1978, Dressler & Gunn 1983). As recent investigations indicate, these objects are unlikely to end as massive Es. HST imaging shows that most blue cluster galaxies and a significant fraction of E+A galaxies are in fact infalling spirals or irregular galaxies (Dressler et al. 1994, Wirth et al. 1994, Belloni et al. 1997), possibly experiencing tidal shaking or 'harrassment' (Moore, Katz, Lake 1996). Only a small percentage of these objects are merg-

ers. The outer parts of the disks are stripped during this process and/or star formation may enhance the inner stellar densities. Large disk-to-bulge ratios are transformed into low disk-to-bulge ratios, i.e., early spirals may turn into S0 galaxies or, maybe, disk Es, late spirals possibly into dwarf Es. Today, all these objects will have only modest luminosities and do not enter the ballpark of giant Es. At modest luminosities, however, S0s and disk Es are indeed the dominant galaxy population in present-day clusters (e.g., Saglia et al. 1993, Jørgensen et al. 1994).

As this discussion shows, the conclusions derived from the redshift evolution of Es are in good agreement with the stellar population properties of local Es.

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